



Gauge Boson production at the Tevatron

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We present measurements on gauge boson production from data taken during 1994-1996 by the DØ and CDF detectors: the differential production cross section of the W boson as a function of the transverse momentum [1,2], the ratio of W and Z differential cross sections [3,4], direct photon cross-sections at $\sqrt{s}=630$ and 1800 GeV [5,6], and studies of Drell-Yan production [7,8]. All measurements are in good agreement with currently available theoretical predictions in most of the measured kinematic range.

1. The W boson Differential Production Cross Section

Measurement of the differential cross section for W boson production provides an important test of our understanding of quantum chromodynamics (QCD). Its implications range from impact on the precision determination of the W boson mass to background estimates for new physics phenomena.

When the transverse momentum (p_T^W) and the invariant mass (M_W) of the W boson are of the same order, the production rate can be calculated perturbatively order by order in the strong coupling constant α_s . For $p_T^W \ll M_W$, the calculation is dominated by large logarithms $\approx \alpha_s \ln(M_W/p_T^W)^2$, which are related to the presence of soft and collinear gluon radiation. Therefore, at sufficiently small p_T^W , fixed-order perturbation theory breaks down and the logarithms must be resummed. The resummation can be carried out in transverse momentum (p_T) space or in impact parameter (b) space via a Fourier transform. Differences between the two formalisms are discussed in Ref. [9].

Although resummation extends the perturbative calculation to lower values of p_T^W , a more fundamental barrier is encountered when p_T^W approaches Λ_{QCD} , the scale characterizing QCD processes. The strong coupling constant α_s becomes large and the perturbative calculation is

no longer reliable. The problem is circumvented by using a cutoff value and by introducing an additional function that parameterizes the non-perturbative effects [10,11].

The inclusive differential cross section for W boson production is measured in the electron channel as a function of transverse momentum. We use 85 pb⁻¹ of data recorded with the DØ detector during the 1994-1995 run of the Fermilab Tevatron $p\bar{p}$ collider.

The $W \rightarrow e\nu$ event sample is corrected for kinematic and geometric acceptance, and detector resolution. The final results for $d\sigma(W \rightarrow e\nu)/dp_T^W$ are plotted in Fig. 1, where the data are compared to the combined QCD perturbative and resummed calculation in b -space, computed with published values of the non-perturbative parameters [10]. The error bars on the data points correspond to their statistical uncertainties. The fractional systematic uncertainty is shown as a band in the lower portion of the plot, and accounts for the errors in the hadronic energy scale and resolution, the selection efficiency, and the background. An additional normalization uncertainty of $\pm 4.4\%$ from the integrated luminosity is not included in any of the plots.

2. W and Z p_T Ratio Measurement

For the analyses of data taken during 1992-1996 (Fermilab Tevatron Run 1), we have used the resummed calculation of Ref. [10] fitted to

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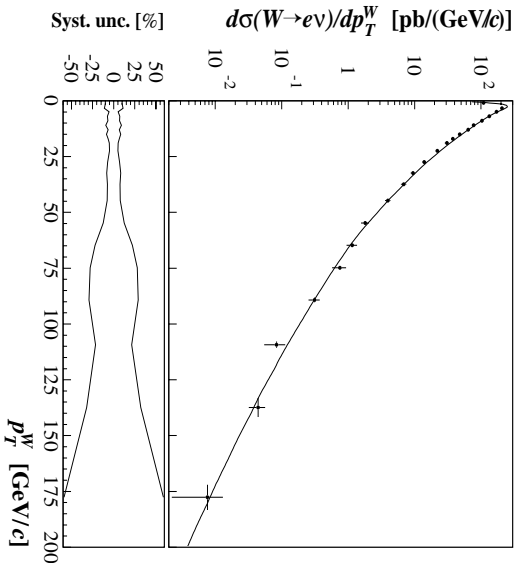


Figure 1. Differential cross section for $W \rightarrow e\nu$ production.

our observed $Z \rightarrow e^+e^-$ differential cross section to extract the non-perturbative phenomenological parameters of the theory. The resummed calculation was then used to predict W boson observables such as the electron and neutrino transverse momenta and as input to a Monte Carlo model of W boson production and decay, which we used to extract the mass and production cross section of the W boson.

Ref. [14] proposes an alternative method of predicting W boson observables from measured Z boson quantities. This is based on the theoretical ratio of the W to Z boson differential cross sections with respect to variables that have been scaled by their corresponding vector boson masses. Because production properties of W and Z bosons are very similar, the large radiative corrections that affect the individual distributions cancel in the ratio. The ratio can therefore be calculated reliably using perturbative QCD (pQCD), with no need for resummation.

Although the alternative method reduces both the theoretical and experimental systematic uncertainties, it introduces a statistical contribution

to the uncertainty from the number of events in the Z boson candidate sample. Hence, once large samples of Z boson events become available, it is expected that using the pQCD prediction and the well-measured p_T^Z distribution to predict the p_T^W distribution should lead to smaller overall uncertainties on the measured mass and width of the W boson, relative to current methods used at hadron colliders.

The ratio of differential cross sections for the scaled W and Z boson transverse momenta (p_T^W/M_W and p_T^Z/M_Z) is defined as

$$R_{p_T} = \left[\frac{d\sigma^W}{d(p_T^W/M_W)} \right] / \left[\frac{d\sigma^Z}{d(p_T^Z/M_Z)} \right], \quad (1)$$

where $d\sigma^V/dp_T^V$ is the standard differential cross section for vector boson production $\sigma(p\bar{p} \rightarrow V + X)$ as a function of transverse momentum p_T^V . Equation 1 can be used to predict the differential cross section for W bosons with respect to the non-scaled transverse momentum:

$$\left. \frac{d\sigma^W}{dp_T^W} \right|_{\text{predicted}} = \frac{M_Z}{M_W} \times R_{p_T} \times \left. \frac{d\sigma^Z}{dp_T^Z} \right|_{\text{measured}}^{p_T^Z = \frac{M_Z}{M_W} p_T^W}, \quad (2)$$

where R_{p_T} is calculated using pQCD. The measurement of R_{p_T} is compared to the calculation of Ref. [14]. For completeness, we repeat the exercise presented in Ref. [14] and use our measured differential Z boson cross section in Eq. 2, and R_{p_T} from Ref. [14], to obtain the differential W boson cross section and compare it to our published result [1].

From the measured W and Z boson differential cross sections, we extract the ratio of scaled cross sections as a function of p_T , R_{p_T} . The result is shown in Fig. 2. We observe that the measured R_{p_T} agrees with the pQCD prediction [14]: the χ^2 for the comparison between data and theory is 18.3 for 21 degrees of freedom (63% probability).

Based on Eq. 2, we use the calculated R_{p_T} in Ref. [14], together with the measured $d\sigma^Z/dp_T^Z$, to predict the W boson transverse momentum spectrum, and compare it with our previously measured $d\sigma^W/dp_T^W$ [1]. Fig. 3 shows the measured differential cross section plotted at the center of the bin. The upper and lower 68% confidence level limits for the prediction are plotted as

histograms. The extracted transverse momentum distribution agrees well with the measurement.

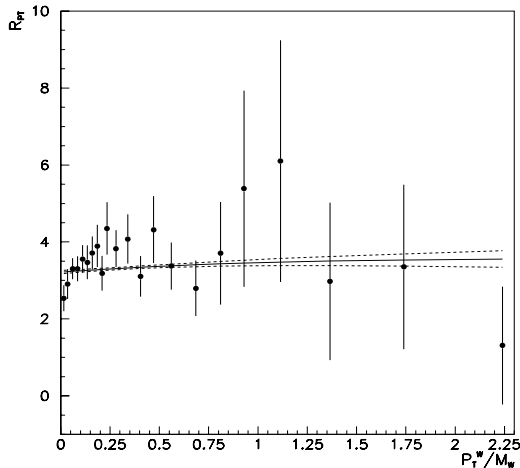


Figure 2. Ratio of scaled differential cross sections R_{p_T} for W and Z production.

3. Direct Photon Cross Sections at $\sqrt{s} = 630$ and 1800 GeV

Within the framework of Quantum Chromodynamics (QCD), isolated single photons are direct photons: produced from the primary parton-parton interactions. A measurement of the final state photons provides a probe of QCD without additional complications from fragmentation and jet identification, providing a powerful and effective means for studying the constituents of hadronic matter.

Previous experiments, at center-of-mass energies of both 630 GeV [16] and 1800 GeV [17,18], have reported photon production in excess of next-to-leading-order (NLO) QCD predictions at low transverse energies ($E_T^\gamma \sim 30$ GeV). This disagreement with data could result from gluon radiation not included in NLO calculations or because the parton distributions are not well known.

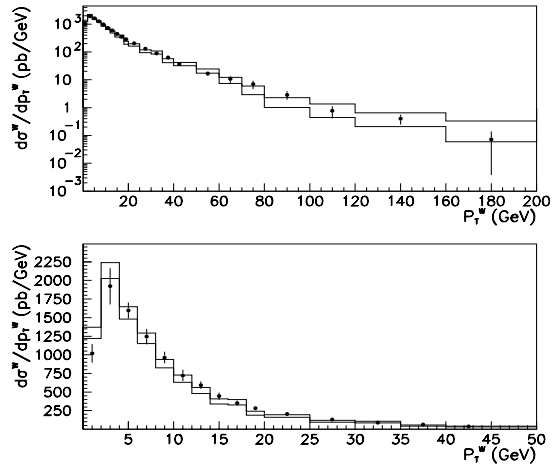


Figure 3. Differential cross section for W boson production as a function of p_T^W .

We present a measurement [5] of the ratio of isolated photon cross sections at different center-of-mass energies, 630 and 1800 GeV by the DØ experiment. The systematic uncertainty and the sensitivity to the choice of parton distribution functions (PDF) are significantly reduced in the ratio. Photon candidates are required to have calorimeter shower characteristics consistent with that of a single electron, and must not have a track match in the drift chamber.

In the simple parton model, the dimensionless cross section $E_T^4 \cdot E \frac{d^3\sigma}{dp^3}$, as a function of $x_T = \frac{2E_T}{\sqrt{s}}$, is independent of \sqrt{s} . Although deviations from such naive scaling are expected, the dimensionless framework provides a useful context for comparison with QCD. The experimental dimensionless cross section, averaged over azimuth, becomes $\sigma_D = \frac{E_T^4}{2\pi} \cdot d^2\sigma/dE_T d\eta$. The ratio $\sigma_D(\sqrt{s} = 630 \text{ GeV})/\sigma_D(\sqrt{s} = 1800 \text{ GeV})$ is determined by combining the cross section reported here with the DØ measurement at $\sqrt{s} = 1800$ GeV [17]. The ratio is shown as a function of x_T in Fig. 4 together with the NLO QCD prediction.

The probability of agreement from a χ^2 test between data and theory is 49% (89%) in the CC (EC) region. The deviations at low x_T are not significant in light of our combined statistical and systematic uncertainties, and there exists good agreement between the measured ratio and theory.

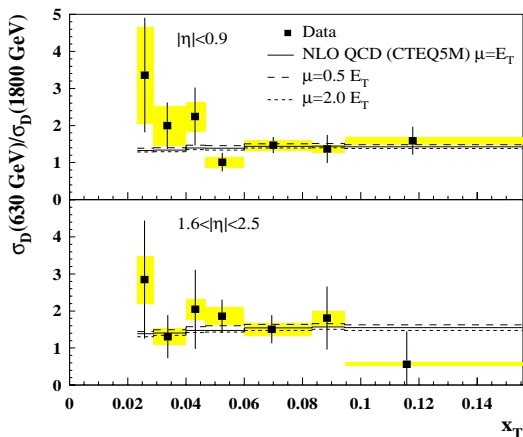


Figure 4. The ratio of the dimensionless cross sections, $\sigma_D(\sqrt{s} = 630 \text{ GeV})/\sigma_D(\sqrt{s} = 1800 \text{ GeV})$ in the central (upper) and forward (lower) rapidity regions.

CDF has measured [6] the cross sections $d^2\sigma/dP_T d\eta$ for production of isolated direct photons at two center of mass energies (1800 and 630 GeV). Figure 5 shows these results as a function of the scaling variable x_T . One observes a significant disagreement in the ratio that is difficult to explain with conventional theoretical uncertainties such as scale dependence and parton distribution functions. However, one possibility for the observed discrepancy with NLO QCD is the lack of a complete description of the initial state parton shower in the NLO QCD calculation, which could give a recoil effect to the photon+jet system

(k_T). To test this hypothesis, a simplified gaussian smearing was added to the NLO QCD calculation, giving the photon+jet system a transverse momentum recoil consistent with that measured in the Drell-Yan process at each center of mass energy. The comparisons of the prediction with the measured ratio are significantly improved with the addition of these amounts of k_T . Higher order QCD calculations including such effect are becoming available [21], but are not ready for detailed comparisons at this time.

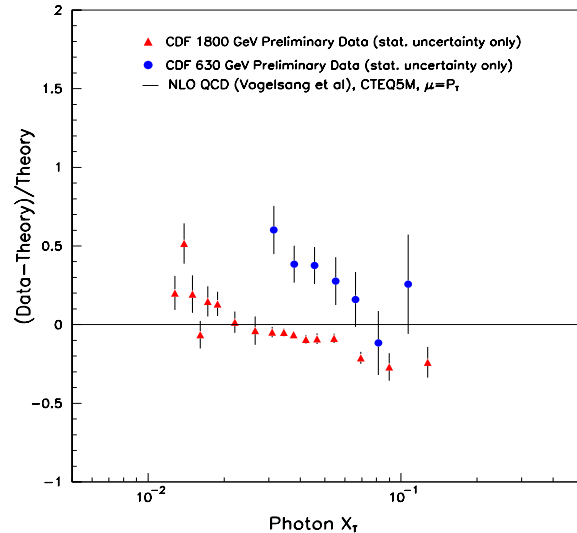


Figure 5. Comparison of 1800 and 630 GeV direct photon data to NLO QCD calculation as a function of photon x_T .

4. Studies of high mass Drell-Yan pairs

We present a new measurement [7] of the mass dependence of the forward-backward asymmetry (A_{FB}), and production cross section ($d\sigma/dM$) for e^+e^- pairs with mass $M_{ee} > 40 \text{ GeV}$ from 108 pb^{-1} of data taken by the CDF Collaboration during 1992-1995. The measurements are compared to predictions from the Standard Model

and from a model with an additional Z' gauge boson. Previous measurements by CDF [22] restricted the data to central rapidity leptons (electrons or muons) and measured the $d^2\sigma/dM dy$ averaged over central rapidities. This new result includes electrons in the forward calorimeters, new techniques to reduce the backgrounds from QCD processes, and reports on measurements of A_{FB} in small bins over a large range in mass (from 40 to 500 GeV).

Figure 6 compares the measured $d\sigma/dM$ and A_{FB} to theoretical predictions. The upper plot shows $d\sigma/dM$ for e^+e^- pairs for both the CDF and DØ collaborations, and $\mu^+\mu^-$ pairs from CDF. The lower plot shows the A_{FB} measurement in the e^+e^- channel from CDF. The Standard Model NNLO prediction is shown as a solid line. The data is in good agreement with the Standard Model predictions. However, the measured A_{FB} is 2.2σ below the Standard Model prediction in the highest mass bin, from 300 to 600 GeV. From the four events in the sample, three are in the negative hemisphere. A negative asymmetry in this region could result from a new interaction not included in the Standard Model. As one possible example of additional interactions that could be compatible with the measured A_{FB} , we show in Fig. 6 predictions that include an additional E_6 Z' boson, with a width of 10% its mass, for two masses of 350 GeV and 500 GeV respectively. Although both CDF and DØ have set limits on the mass of additional Z' bosons of the order of 600 GeV [22,23] those were based on assuming a narrower Z' ($\Gamma_{Z'} \approx 0.01 M_{Z'}$) with the same couplings to the three generations than the Standard Model Z boson. Allowing for additional decay modes with larger couplings to third generation reduces the direct limits by 100 to 150 GeV [24]. The high mass Drell-Yan data will be included in global fits to electroweak data to search for physics beyond the Standard Model.

In addition, we have measured [8] $d\sigma/dy$ over nearly the entire kinematic region of rapidity for e^+e^- pairs in both the Z -boson mass region, and the high mass mass region of $M_{ee} > 116$ GeV/ c^2 . Previous measurements were performed in the central rapidity production region, and a model dependent extrapolation to the forward rapidity

region was needed to extract the total cross section for hard processes such as top quark and W or Z boson production. Fig. 7 shows the measured $d\sigma/dy$ distribution for e^+e^- pairs in the Z boson mass window of $66 < M_{ee} < 116$ GeV/ c^2 . The theoretical expectation is consistent with the measurement.

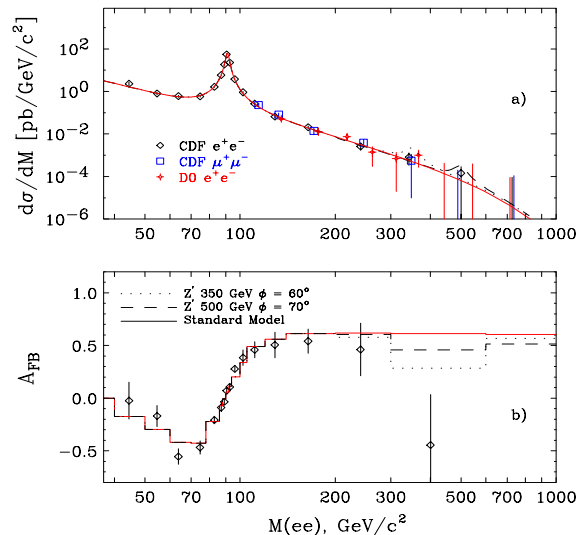


Figure 6. $d\sigma/dM$ (top) and A_{FB} (bottom) distributions from data compared to predictions from the Standard Model (solid line), and a model that includes an extra E_6 Z' boson with $M_{Z'} = 350(500)$ GeV shown as dotted (dashed) lines.

5. Summary and Prospects

Recent results on gauge boson production from DØ and CDF Run 1 data are in good agreement with theoretical predictions. The deviations at low p_T are not significant. The study of the W , Z , and γ production mechanisms is important as a direct test of the standard model, to improve the understanding of the background in top quark and Higgs boson production, as well as to control the systematics in precision measurements

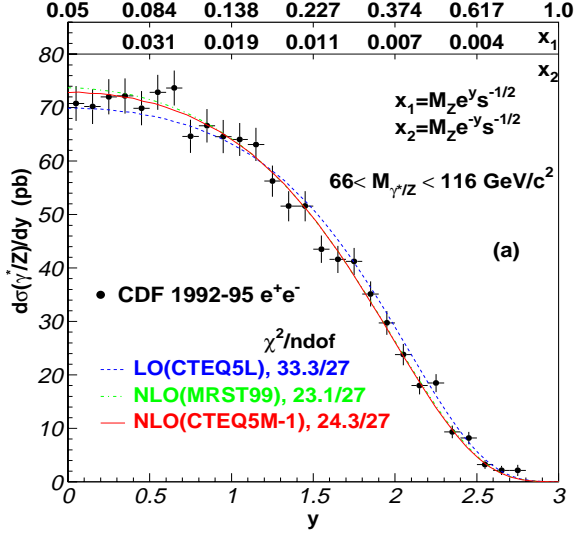


Figure 7. $d\sigma/dy$ for $e^+ e^-$ pairs in the Z boson mass window.

such as the W mass. Run 2 has started and we expect 2 fb^{-1} of data by year 2003. The much larger number of gauge bosons will allow us to reduce systematics in both the measurements and the predictions. We will also be able to reduce uncertainties in the direct photon cross sections (dominated by the photon purity of the sample), as well as to extend the kinematic range of the measurement.

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